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Impurity Transport During Neutral Beam Injection in the ISX-B Tokamak

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MASTER

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DEPARTMENT OF ENERGY

ORNL/TM-7472
Dist. Category UC-20 f

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

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Date Published - October 1980

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ABSTRACT

In ohmically heated ISX-B discharges, both the intrinsic iron impurity ions and small amounts of argon introduced as a test gas accumulate at the center of the plasma. But during certain beam-heated discharges, it appears that this accumulation does not take place. These results may reflect the conclusion of Stacey and Sigmar that momentum transferred from the beams to the plasma can inhibit inward impurity transport.

IMPURITY TRANSPORT DURING NEUTRAL BEAM INJECTION IN THE ISX-B TOKAMAK

One of the concerns about the use of neutral beam injection as a method of auxiliary heating in tokamaks is that additional impurities may be introduced into the discharge due to sputtering by high energy atoms or ions. However, Stacey and Sigmar[1] have shown theoretically that the consequences of this effect may be ameliorated by a reduction of the radial impurity influx due to the momentum which the beams transfer to the plasma. For a single impurity species, they demonstrate that although the direct influence of coinjection (in the direction of the plasma current) on the impurity is to enhance its inward transport,[2] the first-order flows in the flux surfaces are simultaneously altered in such a way that outward transport may be the net result. We analyze spectral data from two sequences of discharges in the Impurity Study Experiment (ISX-B) tokamak which indicate that during injection the impurity influx is indeed strongly reduced, or even reversed, in the inner half of the plasma.

The plasmas we discuss here are produced in deuterium with an ohmic heating current of 110 kA. For the injection case, 500 kW of neutral hydrogen is injected between 70 and 170 ms in discharges which last a total of 200 ms. The electron heating produced by the beam results in a central temperature of 1400 eV, as contrasted with 750 eV for the non-injected case. In all instances deuterium gas is bled into the discharge from 30 ms until the end of the shot in order to raise the electron concentration. The time behavior of $\overline{n_e}$ is shown in Fig. 1. Without injection, the density continues to rise until the plasma disrupts around 150 ms. With injection, the density "clamps" at 110 ms and no disruption occurs. This clamp is characteristic of most injection discharges in ISX-B.[3] Although the total electron concentration is limited, the radial profiles are not strongly affected. The mechanism by which clamping occurs is not understood, but it may reflect an alteration in the basic transport processes such as we discuss for the impurities.

The temporal evolutions of two argon lines[4] are shown in Fig. 2. Argon is introduced in a short (∿4-ms) puff at 100 ms, and the integrated radiation along a central chord is observed. Extensive use is made of the RECYCL code[5] to analyze spectral data. This code enables us to calculate the radial distributions of line emissions of various ionization stages for assumed total impurity profiles and transport velocities. The Ar VII line is computed to be emitted from a shell about 2 cm wide centered near 20 cm (the plasma minor radius is 26 cm). In both injection and noninjection discharges, the Ar VII radiation attains a constant level within a few milliseconds of introducing the gas. This behavior is indicative of a constant flux through the plasma periphery during the entire shot, i.e., of anomalous outward diffusion that causes the argon to recycle rapidly in the edge.[6]

The Ar XVI line exhibits strikingly different behavior for the two sequences of shots. It is emitted mainly inside a radius of 13 cm, and calculations using transport velocities of 1-2 cm/ms, to agree with the observed onset of the radiation, indicate that significant emission from Ar XVI should take place from the plasma center in both cases. This lithium-like ion thus provides a useful monitor of the argon concentration in the interior of the discharge. It is seen in Fig. 2 that during injection the Ar XVI radiation, similar to the Ar VII radiation, reaches a steady state. The relative intensities indicate that the argon distribution is not strongly peaked at the center. In contrast, there is a continued rise in the Ar XVI signal without injection. This rise is much larger than can be explained by the increasing electron concentration, and it indicates that, even in view of the rapid recycling at the plasma edge, there is a slow, continual accumulation of argon in the plasma interior. Therefore, it appears that the presence of neutral beam injection does alter the transport sufficiently in the interior of the plasma to prevent accumulation of the test impurity. -

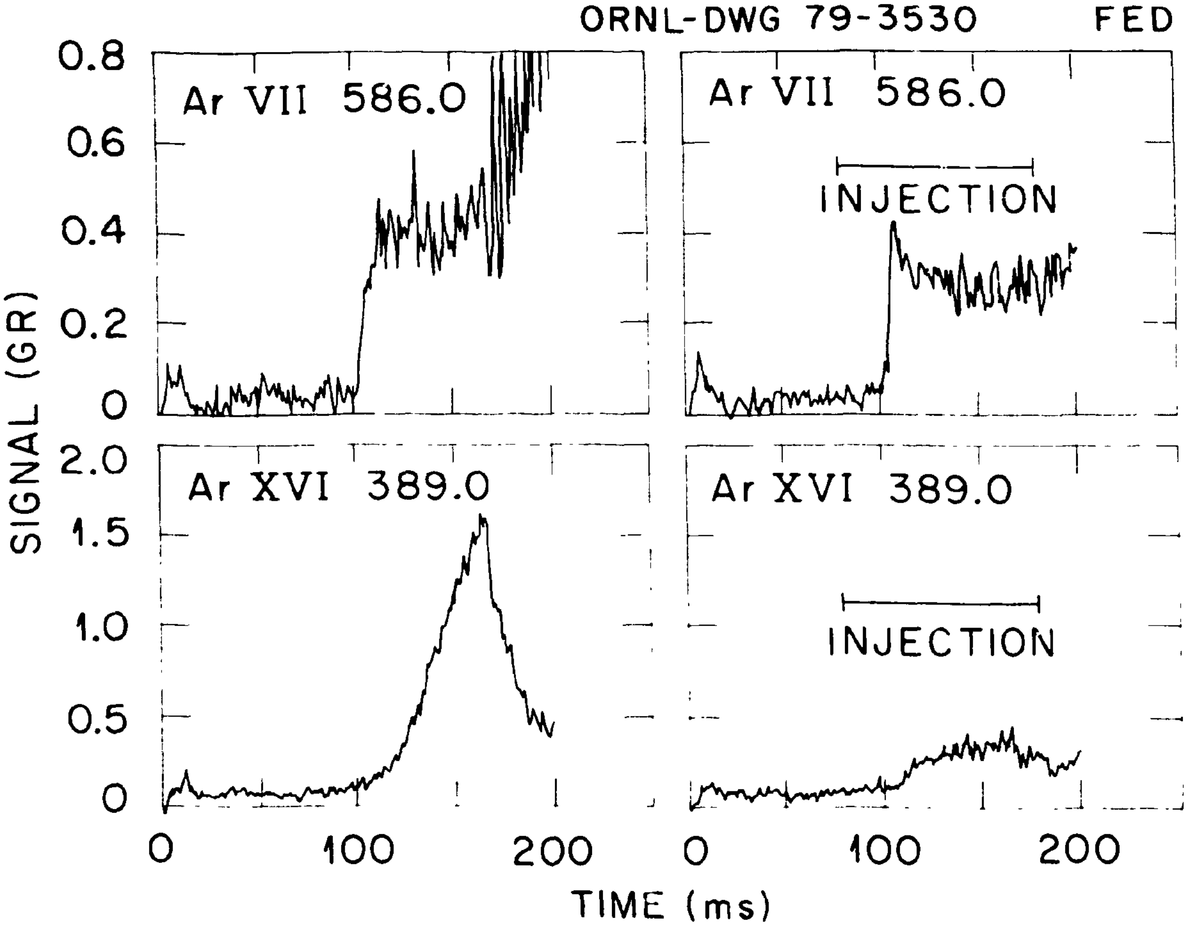

Fig. 2. Spectral emissions from Ar VII and Ar XVI. The argon is introduced into the plasma in a 4-ms burst at 100 ms after breakdown.

We have also analyzed the iron radiation from the same sequences for which the argon was studied. Figures 3 and 4 illustrate the time behavior of several spectral lines. Again it is observed that the interior ions, such as Fe XVIII and Fe XIX, evidence accumulation in the ohmic heating case but that the intensities during injection are quite low. Also, the Fe XX radiation is barely above the background level, even though this ion should be abundant at the electron temperatures achieved during injection. In contrast, it is immediately obvious that the iron concentration in the exterior of the plasma rises shortly after injection; for a fixed iron density profile. the radiation from stages such as Fe IX would be expected to decrease by a factor of about three since this ion radiates from a much narrower shell in the hotter plasma.

It is possible to obtain quantitative, although not highly accurate, assessments of the total iron behavior throughout the plasma volume by adjusting profiles in the RECYCL code until satisfactory agreement is obtained between computed and measured emission rates. The accuracies of the individual computed rates are believed to be no better than a factor of two due to uncertainties in the atomic physics and in the transport velocities of the impurities. The calibration of the monochromator introduces an additional uncertainty in the interpretation of the data, and we estimate that our inferred profiles may be in error by a factor of three.

The profiles obtained for the two sequences at 141 ms are shown in Fig. 5. The noninjection concentration peaks at the center, as might be expected. However, there appears to be no way to explain the data obtained during injection without inferring a profile that has a maximum near one-half of the plasma minor radius. If the iron concentration is assumed to be nondecreasing inside 15 cm, radiation from Fe XIX and Fe XX should be respectively five and ten times the observed values. Consequently, the iron profile must be "hollow," and even if there is a larger influx of iron during injection, it must accumulate at some intermediate radius. Despite the problems inherent in inferring radial concentrations from line-averaged data, it seems that the profiles of Fig. 5 are at least qualitatively correct.

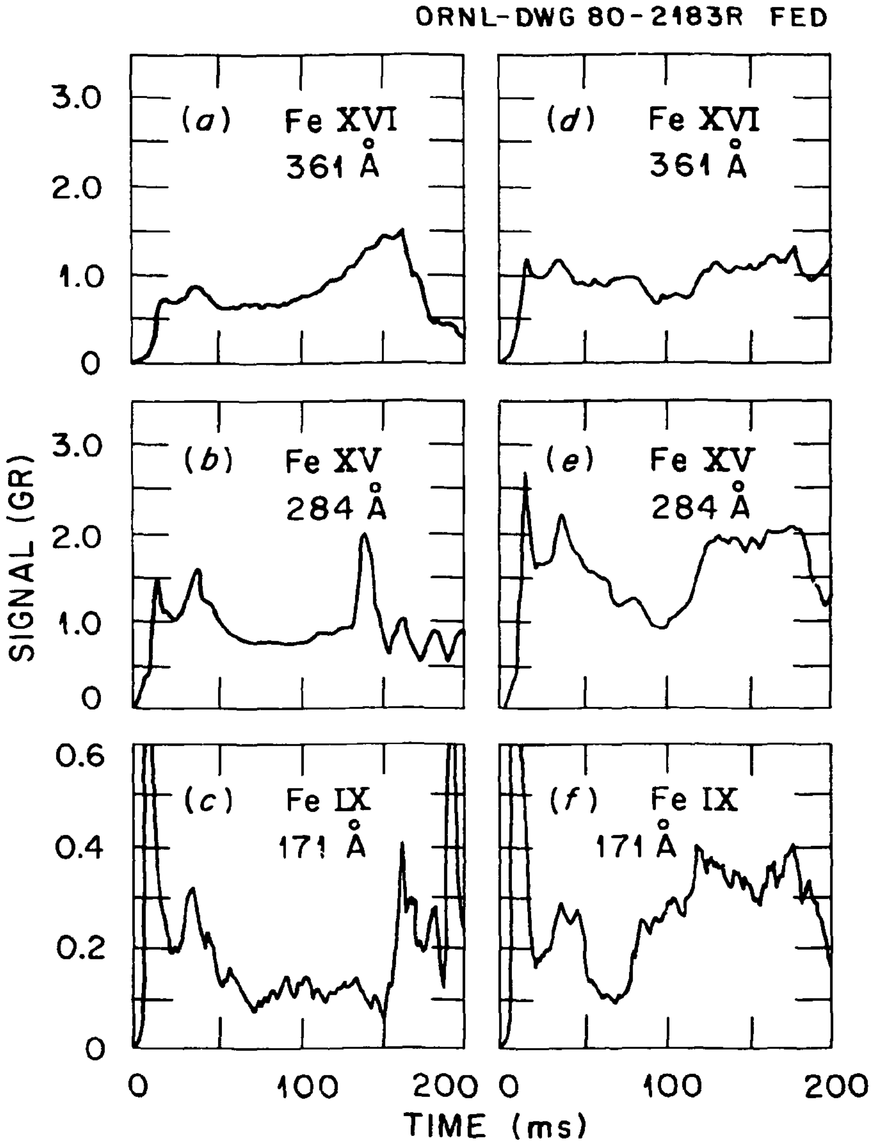

Fig. 3. Comparison of emissions from Fe IX, Fe XV, and Fe XVI. Figures 3(a)-3(c) are without injection; Figs. 3(d)-3(f) are with injection. Injection lasts from 70-170 ms.

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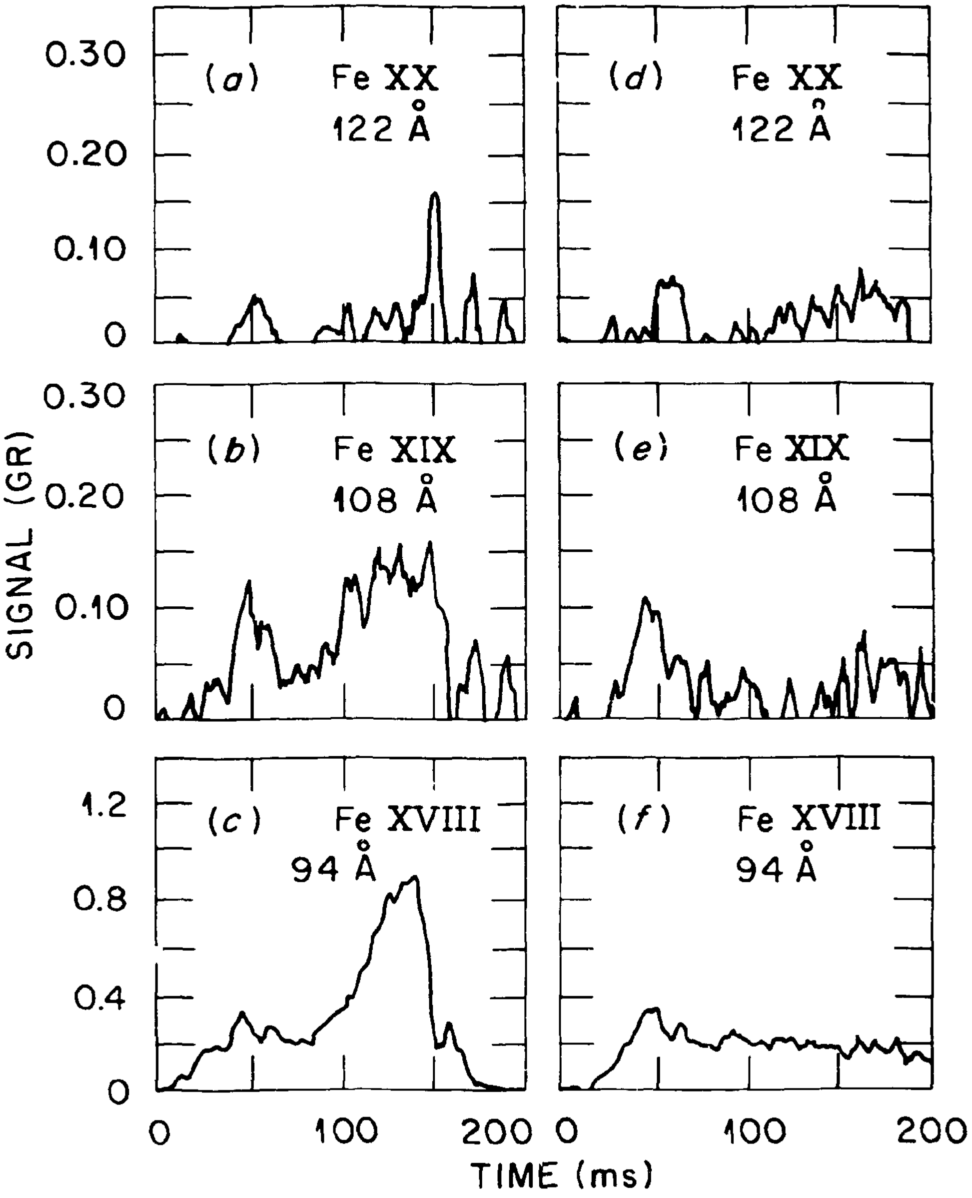

Fig. 4. Comparison of emissions from Fe XVIII, Fe XIX, and Fe XX. Figures 4(a)-4(c) are without injection; Figs. 4(d)-4(f) are with injection. Injection lasts from 70-170 ms.

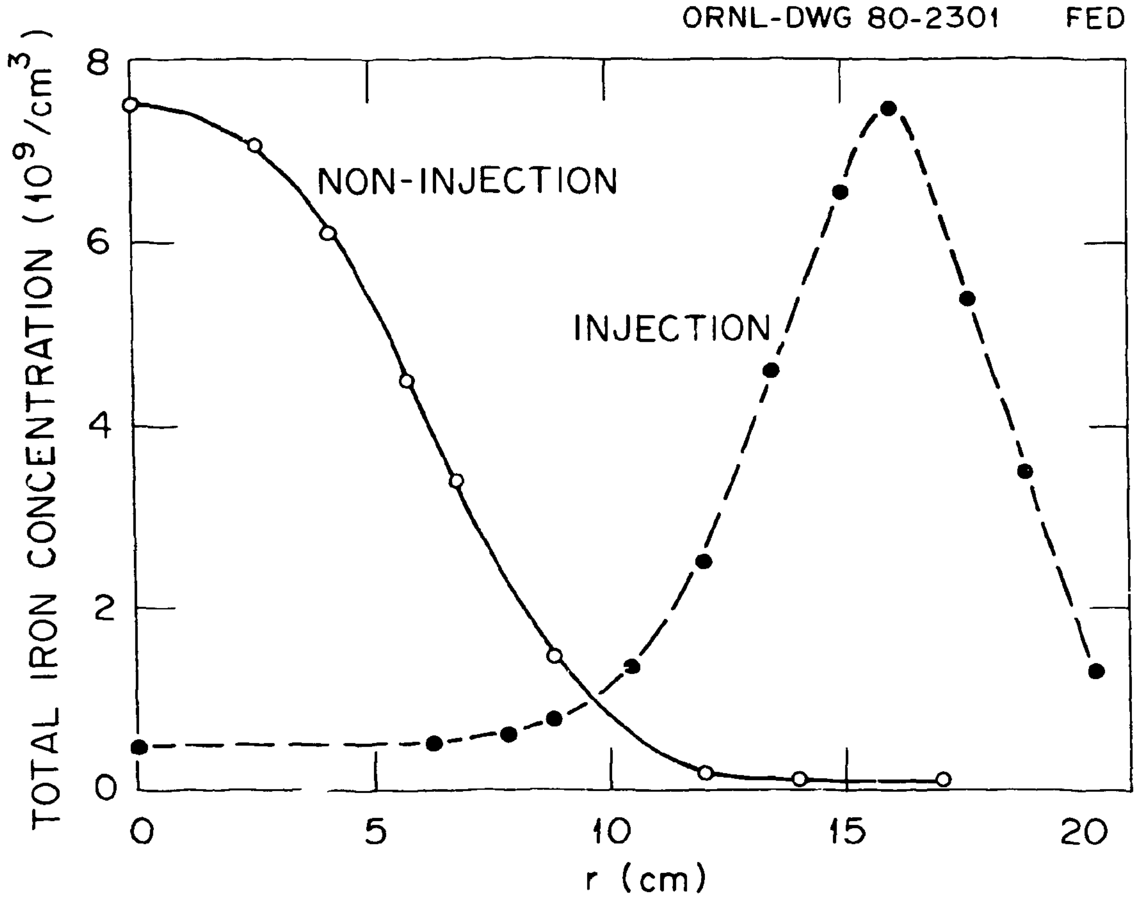

Fig. 5. Profiles of total iron concentration with injection (dashed line) and without injection (solid line).

Direct comparisons of our analysis with the theory of Stacey and Sigmar are not possible at present. The detailed physics of the external drag terms that appear in their formalism is not well understood, and in reality we must consider a multicomponent rather than a two-component plasma (oxygen and carbon are the dominant impurities). However, it is worth examining their criterion for flow reversal under the assumption that the theoretical terms containing the beam momentum transferred to the plasma ions dominate those which contain the momentum transferred to the impurities. In this case, the requirement as a function of plasma radius can be expressed as

$$I_b H(r) > \frac{n_i m_i \nu_{iz} \left| \frac{1}{Z_i n_i} \frac{\partial P_i}{\partial r} \right| 2\pi R_o}{m_b v_b \left| B_{po} \right|} \cdot \frac{\beta_z}{\beta_i (1 + \beta_z) + \beta_z} \qquad (1)$$

in the mixed collisionality regime of the ISX experiments. Here, I_b is the total neutral beam current, H(r) is the normalized power deposition profile, and β_i and β_z respectively represent the ratios of plasma ion and impurity ion drag frequencies to the collision frequency, ν_{iz}. If this inequality is satisfied everywhere in the plasma, then no impurity penetration may be expected from the mechanisms considered in this theory, i.e., from interspecies collisional friction and momentum exchange from external sources. It is also worth noting that both the ion pressure gradient, $\partial P_i/\partial r$, and the poloidal field, B_{po}, approach zero as $r \rightarrow 0$, and in ISX discharges it appears that the former becomes small faster than the latter. In such circumstances the neutral beam requirements may be satisfied for small, but not large, values of r, and hollow impurity profiles could develop in principle. It is evident that our observations are in qualitative agreement with a possible result of Stacey and Sigmar's theory, but because of the uncertainties it cannot yet be said that they substantiate the calculations.

Finally, we note that particle transport problems are so complex that it is impossible to generalize the present results to all, if indeed to many, injection experiments in tokamaks. We believe that a broader scope of both experimental and theoretical studies of the influence of neutral beams on transport must be pursued in order to understand this problem.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions to these studies by all members of the ISX-B Group of the Experimental Confinement Section. Particular thanks are due to M. Murakami, P. W. King, and E. A. Lazarus for Thomson scattering data; to J. B. Wilgen and D. P. Hutchinson for electron concentration data; and to K. H. Burrell for the use of gas injectors provided by the General Atomic Company. W. M. Stacey, Jr., and D. J. Sigmar are credited with motivating the present experiments and their analyses.

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